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Nuclear Reaction Rates and the Nova Outburst

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Classical novae participate in the cycle of Galactic chemical evolution in which grains and metal enriched gas in their ejecta, supplementing those of supernovae, AGB stars, and WR stars, are a source of heavy elements for the ISM. Once in the diffuse gas, this material is cycled through molecular clouds before being incorporated into young stars and planetary systems during star formation. Infrared observations have confirmed the presence of carbon, SiC, hydrocarbons, and oxygen-rich silicate grains in nova ejecta, suggesting that some fraction of the pre-solar grains recently identified in meteoritic material may come from novae. The mean mass returned by a nova outburst to the ISM probably exceeds $\sim 2 \times 10^{-4}$ $M_\odot$. Using the observed nova rate of 35±11 per year in our Galaxy, it follows that novae introduce more than $\sim 7 \times 10^{-3}$ $M_\odot$ yr^{-1} of processed matter into the ISM. It is likely, however, that novae ejecta are more massive than believed, and this value is a lower limit. Novae are expected to be the major source of ^{15}N and ^{17}O in the Galaxy and to contribute to the abundances of other isotopes in this atomic mass range. In order to understand better their contributions to galactic chemical evolution, we have begun a series of studies with the latest nuclear reaction rate libraries. We report both on how these new rates affect the properties of the outburst and, in addition, how they change the predictions of the contributions of novae to Galactic chemical evolution.

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1. Introduction

Observational and theoretical studies of the outbursts of classical novae have provided critical insights into a broad range of astrophysical phenomena. Thermonuclear runaways (TNRs) in accreted hydrogen-rich envelopes on the white dwarf (WD) components of close binary systems constitute not only the outburst mechanism for a classical nova explosion, but also for the recurrent and a fraction of the symbiotic nova explosions. Studies of the general characteristics of these explosions, both in the Galaxy and in neighboring galaxies of varying metallicity, can teach us about binary stellar evolution, while studies of the evolution of nova binary systems can constrain models for the (as yet unidentified) progenitors of Type Ia supernovae. Further, the empirical relation between the peak luminosity of a nova and the rate of decline, which presents a challenge to theoretical models, allows novae to be used as standard candles for distance determinations out to the Virgo Cluster.

Extensive studies of novae with IUE and the resulting abundance determinations have revealed the existence of oxygen-neon-magnesium (ONeMg) WDs in some systems. The high levels of enrichment of novae ejecta in elements ranging from carbon to sulfur confirm that there is significant dredge-up of matter from the core of the underlying WD and enable novae to contribute to the chemical enrichment of the interstellar medium. Observations of the epoch of dust formation in the expanding shells of novae allow important constraints to be placed on the dust formation process and confirm that graphite, SiC, and SiO_2 grains are formed by the outburst (Gehrz et al. 1998; G98 and references therein). It is possible that grains from novae were injected into the pre-solar nebula and can be identified with some of the pre-solar grains or "stardust" found in meteorites (Zinner 1998). Finally, γ-ray observations during the first several years of their outburst done with the next generation of satellite observatories, could confirm the presence of decays from ^{7}Be and ^{22}Na (Weiss and Truran 1990; Nofar et al. 1991; Jean et al. 2000, and reference therein). In the next section we report on new calculations done with the new reaction library of Iliadis et al. (2000). We follow that with a brief discussion of the implications of the new rates for the nova outburst.

2. Evolutionary Sequences Using the Iliadis et al. Reaction Library

Over the past few years we have been exploring the effects of improving the physics in our 1-D hydrodynamic computer code on the simulations of the nova outburst (Starrfield et al. 1998, 2000; S98, S00). As reported in those papers, we have found that improving the opacities, equations-of-state, and the nuclear reaction library have had important effects on both the energetics and the nucleosynthesis. Similar results have been found in the calculations of the Barcelona group as reported elsewhere (Hernanz and Josè 2000, and references therein) and at this meeting. We have now continued our own investigations in this area by using the latest reaction rate library from Iliadis et al. (2000, I2000).

In this study, we used the same 1-D, fully implicit, hydrodynamic computer code which is described in detail elsewhere (S98, S00). In order to test the influence of the new reaction cross sections determined by Iliadis et al. (2000), we have evolved two sets of TNRs on ONeMg WDs. For both $1.25M_{\odot}$ and $1.35M_{\odot}$ WDs, we evolved one sequence using the same reaction rate library as we used in S98 and then evolved a similar sequence

Table 1
Comparison of the Evolutionary Sequences

WD Mass	$1.25 M_\odot$	$1.25 M_\odot$	$1.35 M_\odot$	$1.35 M_\odot$
WD Composition	ONeMg	ONeMg	ONeMg	ONeMg
Reaction Library	old	new	old	new
$T_{peak}(T_6)$	334	328	459	444
$\epsilon_{nuc}(peak)(10^{16}$erg gm^{-1}s$^{-1})$	24	54	230	78
L_{peak} $(10^4 L_\odot)$	28	22	60	50
$M_{acc}(10^{-5} M_\odot)$	6.8	6.8	3.9	3.9
$M_{ej}(10^{-5} M_\odot)$	3	2	3	3
V_{max}(km s^{-1})	2940	2890	6050	4640
^{12}C	1.2×10^{-2}	6.6×10^{-3}	5.0×10^{-3}	1.2×10^{-2}
^{13}C	9.0×10^{-3}	4.0×10^{-3}	2.0×10^{-3}	4.0×10^{-3}
^{14}N	6.9×10^{-3}	1.1×10^{-2}	3.2×10^{-3}	7.6×10^{-3}
^{15}N	7.6×10^{-2}	6.2×10^{-2}	1.1×10^{-1}	9.0×10^{-2}
^{22}Na	1.0×10^{-2}	4.8×10^{-3}	8.8×10^{-2}	3.8×10^{-2}
^{26}Al	2.2×10^{-3}	5.9×10^{-2}	9.5×10^{-4}	2.6×10^{-2}
^{27}Al	2.1×10^{-2}	6.5×10^{-2}	4.0×10^{-2}	1.6×10^{-1}
^{32}S	1.1×10^{-2}	1.7×10^{-4}	2.3×10^{-2}	9.7×10^{-4}

in which the only change was to use the I2000 library. In the cases reported in this paper, we assumed a WD initial luminosity of $\sim 3 \times 10^{-3} L_\odot$ and a mass accretion rate of 10^{16} gm s^{-1} in order to accrete as much mass as possible onto the WD. Here, we were also trying to understand and address the discrepancy between the accreted and ejected mass in our simulations and the observed nova ejecta masses (S98). The results of these calculations can be found in Table 1 and the variations with time of either the temperature in the deepest hydrogen-rich zone or the total nuclear luminosity obtained in our simulations are plotted in Figures 1 to 4. More details of these calculations and additional results for $1.0 M_\odot$ carbon-oxygen WDs will be published elsewhere (Starrfield et al. 2000, in preparation).

Clearly, as shown in both Table 1 and the figures, the gross properties of these sequences are quite similar as we would expect since I2000 made changes in the rates for nuclei only from $20 < A < 40$. We also see that the long understood general properties of the outburst are maintained. That is, the TNR on the more massive WD reaches a higher temperature (~450 million degrees) than that on the lower mass WD (~ 330 million degrees). The same is true for the peak nuclear energy generation (see Table 1) and the peak in the total nuclear energy produced in the evolution (Figure 2 as compared to Figure 4). As seen in Figure 2, the peak in the total nuclear energy generation for the $1.35 M_\odot$ sequence exceeds a value of $10^{13} L_\odot$ while the $1.25 M_\odot$ sequence barely reaches $10^{12} L_\odot$ (Figure 4).

In addition, if we compare these results to those in our earlier studies where we used larger values of the mass accretion rate, we find (as expected) that our new sequences reach higher values of peak temperature (330 million degrees versus 300 million degrees:S00) and higher values of the other gross features of the simulations. (We only have space to show the results for our current studies in this paper.) In Figure 1, we show the variation

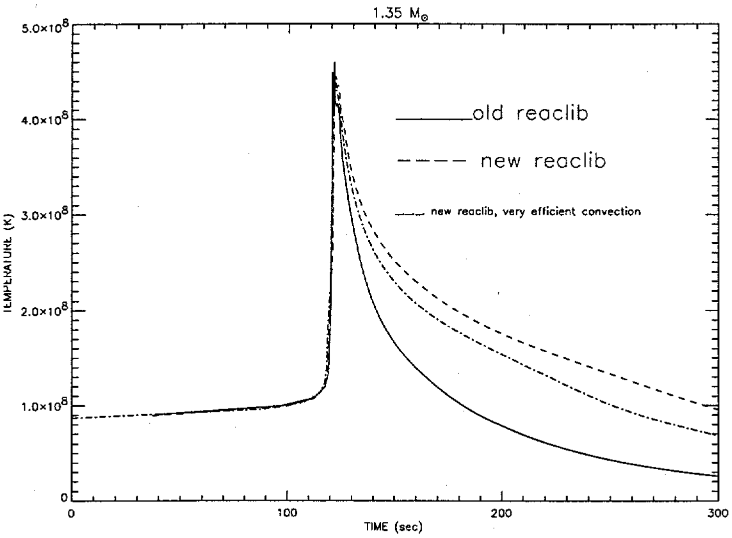

Figure 1. The variation with time of the temperature in the deepest hydrogen-rich zone around the time when peak temperature occurs. We have plotted the results for three different simulations on a 1.35$M_\odot$ white dwarf. The solid line is that for the old reaction library (see S00), the dashed line is that for the simulation using the new reaction library, and the dash-dot line shows the evolution for a simulation in which we have used the new reaction library but increased the ratio of mixing length to scale height to 20 rather than the value of 2 used in our modern simulations.

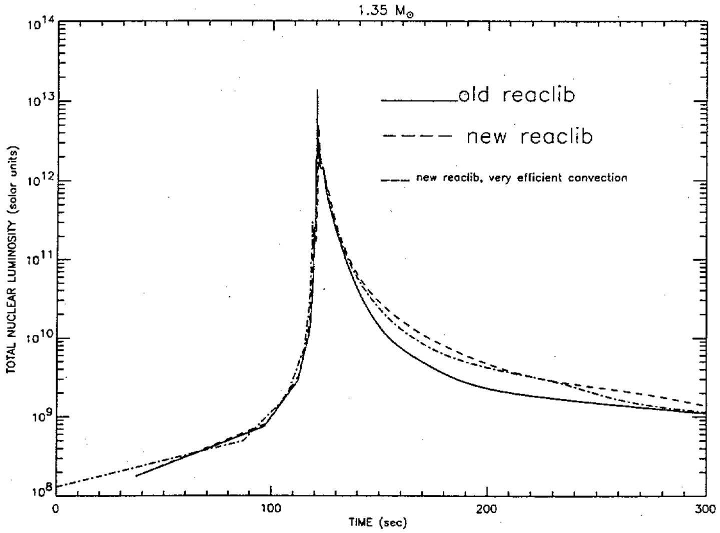

Figure 2. The variation with time of the total nuclear luminosity (erg s^{-1}) in solar units ($L_\odot$) around the time of peak temperature during the thermonuclear runaway on a white dwarf with a mass of 1.35$M_\odot$. We have integrated over all zones taking part in the explosion. The solid, dashed, and dash-dot lines refer to the same simulations shown in Figure 1 as does the time scale.

with time of the temperature in the deepest hydrogen-rich zone around the time of peak temperature. This figure shows three different TNRs. The solid line is taken from the sequence with the old reaction rate library (S00) and the dashed line shows the results from the new reaction library. All other initial parameters are the same. The cause of the slower decline in the temperature for the sequence with the new library is that less energy is produced near maximum so that the model expands and cools less rapidly. The TNR indicated by the dash-dot line was identical to the sequence with the new reaction library but, in order to study the effects of more efficient convection on the evolution, we increased the value of l/h_p(mixing-length to pressure scale height) from our normal value of 2 to 20. This sequence transports more energy to the surface which causes the layers to expand faster which, in turn, causes the deeper layers to expand and cool more rapidly.

Figure 2 shows the variation with time of the total nuclear luminosity (erg $s^{-1}/L_\odot$) for the same TNR as shown in Figure 1. The time scales are the same and we can see that peak nuclear luminosity occurs at the same time as peak temperature. This was not the case for our previous studies where we found that peak nuclear luminosity occurred prior to peak temperature. The higher degeneracy in these sequences, caused by the increased envelope mass, has produced a much more rapid temperature rise than found previously. Of equal importance, the change in reaction libraries has caused more than a factor of 3 decrease in peak nuclear luminosity. Nevertheless, the values shown in this paper exceed our previous results by nearly a factor of 10. When the energy produced by these TNRs reaches the surface, the peak luminosity exceeds L_{Edd} by a large factor (see Table 1) but not for as long as is observed in some novae (Schwarz et al. 2000; Shaviv 2000, preprint). This is another discrepancy between theory and observations that must be resolved if we are to claim that we fully understand the nova outburst. Figures 3 and 4 show the variation in the temperature and nuclear luminosity for TNRs on $1.25M_\odot$ WDs and these results should be compared to the calculations reported in S98 and S00.

When we examine the entries in Table 1 for the effects of changing the reaction library on the peak in nuclear energy generation, we see a decrease from 2.3×10^{18} erg gm^{-1} s^{-1} to 7.8×10^{17} erg gm^{-1} s^{-1}. This decline is caused by a reduction in the cross sections for many of the proton-capture nuclei with masses exceeding ^{26}Al. Therefore, the enhanced energy production from proton captures on more massive nuclei is not present in the sequences evolved with the new reaction library. The effects of the smaller cross sections can be seen in the abundance of ^{26}Al which is nearly 30 times higher in the $1.35M_\odot$ sequence with the new library and the abundance of ^{27}Al which increases by a factor of 4 in the $1.35M_\odot$ simulation (see Table 1). The increase in the aluminum abundance (both ^{26}Al and ^{27}Al) also occurred in the $1.25M_\odot$ sequence which only reached a peak temperature of $\sim$330 million degrees. In contrast, the abundance of ^{22}Na declines for both WD masses as a result of changing the library. This suggests that our previous claims that ^{26}Al was preferentially produced in TNRs on low mass WDs and ^{22}Na on high mass WDs must be changed. In fact, it now appears that significant amounts of ^{26}Al are produced at all WD masses above $1.0M_\odot$. (We have not yet evolved an ONeMg sequence on a $1.0M_\odot$ WD so this statement needs to be checked.)

It is disturbing that the abundance of ^{22}Na has dropped by more than a factor of 2 at both masses that we studied. This suggests that our predictions for γ-ray emission from novae and those of Jean et al. (2000) need to be redone. Finally, we also tabulate

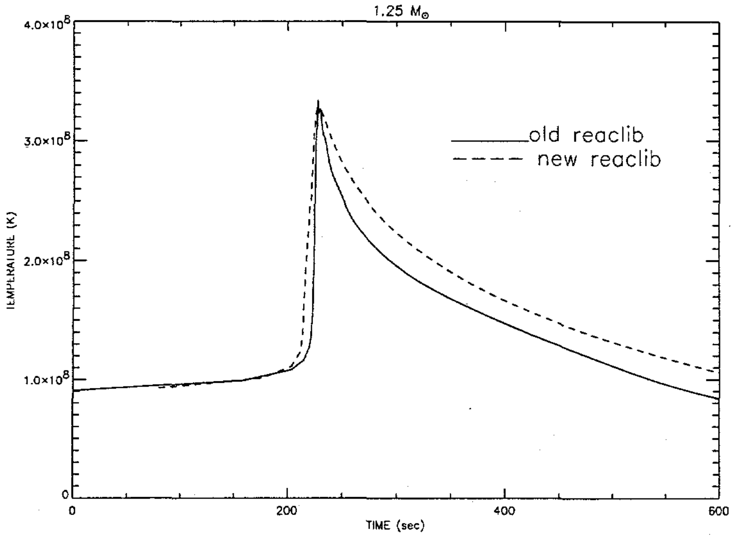

Figure 3. Same as for Figure 1 but for a white dwarf mass of $1.25M_\odot$. Note that we did not plot the sequence with enhanced convection.

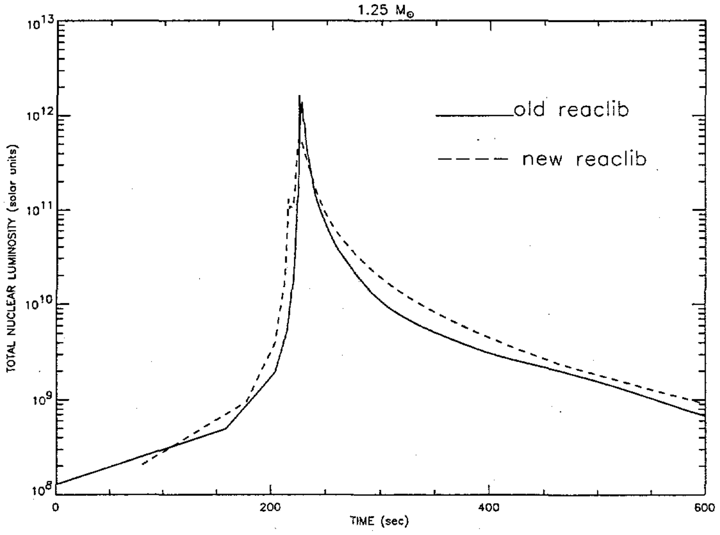

Figure 4. Same as for Figure 2 but for a white dwarf mass of $1.25M_\odot$. Note that we did not plot the sequence with enhanced convection.

the abundance of ^{32}S in Table 1 in order to show that there is a significant decrease in the abundances of the higher mass nuclei when we switch to the I2000 reaction library. This result only underscores our statement that most of the proton captures end at about aluminum. We will provide a full tabulation of the final abundances for all the nuclei in our network elsewhere (Starrfield et al. 2000, in preparation). We find, however, that for most cases the abundances of the nuclei more massive than aluminum decrease when we switch to the new library.

Of further interest in these calculations is that in all sequences the ejected abundance of ^{15}N exceeds that of ^{14}N by a large factor. For example, in the 1.35$M_\odot$ sequence (using the old library) more than 10% of the ejecta (by mass) is ^{15}N and its abundance exceeds that of ^{14}N by over a factor of 30. While similar results were found in our earlier studies of TNRs on 1.25$M_\odot$ WDs (S98; S00), the overproduction of ^{15}N was not as extreme (factors of 7 or less). One important cause of this change is that the rates of the ^{13}N(p,γ), ^{17}F(p,γ), ^{18}F(p,γ), and ^{18}F(p,α) reactions were changed in I2000. Another cause of the abundance changes must be the higher peak temperatures reached in these simulations as compared to those in our previous work. In contrast to the results for oxygen, for all cases the ejected amount of ^{12}C exceeds that of ^{13}C but not by a factor as large as 4 which indicates that the reactions in the TNR were never close to equilibrium.

Finally, we point out that the ejecta velocities for the 1.35$M_\odot$ WD sequences are larger than we have found in our previous studies and approach some of the larger observed velocities in ONeMg nova outbursts (G98). In contrast, the ejecta masses are still too low to agree with observed values. However, they are more than a factor of 10 larger than we found for our earlier sequences (S98;S00). Unfortunately, we have achieved such high values of ejected mass by using mass accretion rates that are far below the observed values.

3. Summary and Discussion

In this paper we examined the consequences of improving the nuclear reaction library on our simulations of TNRs on 1.25$M_\odot$ WD and 1.35$M_\odot$ WDs. We have found that the changes in the rates have affected the nucleosynthesis predictions of our calculations but not, to any great extent, the gross features. In addition, we have used a lower mass accretion rate than in our previous studies in order to accrete (and eject) more material. This has, as expected, caused the peak values of some important parameters to increase over our previous studies at the same WD mass. However, because some important reaction rates have declined in the new compilation this has not increased the abundances for nuclei above aluminum and, in fact, they have declined while the abundances of both ^{26}Al and ^{27}Al have increased at both WD masses. In contrast, the abundance of ^{22}Na has declined at both WD masses over the values predicted in our earlier work. This has important implications with respect to predictions of the observability of novae with INTEGRAL.

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